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Patterns of form error inheritance during machining

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Abstract. The paper studies modeling of quality parameters formation during machining on metal cutting machines. It was demonstrated that operational properties of parts are created not only at finishing operations, but rather formed throughout the entire technological process. At the same time, some characteristics and properties are inherited from operation to operation, i. e. copying of workpiece form errors to the machined part in the form of the same errors. The nonlinearity of the workpiece corresponds to the nonlinearity of the part. The extent of operational copying of nonlinearity (shaft surface runout in the middle section) was studied. A mathematical model of such error inheritance was developed with consideration of the nonlinear approximation of depth of cut variation along the workpiece circumference (per one revolution of the part). For existing tool materials, the exponent x at the cutting depth in the formula of the cutting force P is in the range of 0.7–0.9. As the depth of cut decreases, the refinement coefficient decreases. Therefore, when switching from rough operations (large cutting depths) to finishing (small cutting depths), the refinement coefficient becomes smaller.

1. Introduction

In non-rigid technological systems, a change in the system's elastic deformations causes significant deviations in the form of the machined surface. Errors determined by the elastic deformations of the technological system are dominant in stationary, steady-state mode of operation of the equipment when processing parts with small dimensions. Cutting force induced elastic deformations in the technological system lead to the development of both size errors and form errors of the workpiece [1–4].

When developing a technological process, it must be borne in mind that the operational properties of parts are created not only during finishing operations, but rather throughout the entire technological process. At the same time, some characteristics and properties transition from operation to operation; they seem to be inherited from the previous operation [5–7]. A good example confirming the influence of technological heredity on machining accuracy can be the copying of workpiece form errors to the machined part in the form of the same error (ovality of the workpiece corresponds to the ovality of the part, conicity, cone shape, etc.).

2. Methods

The extent of operational copying of errors is usually expressed through the refinement coefficient

$$K = \frac{\Delta_P}{\Delta_d}$$

where Δ_p – is the error of the workpiece; Δ_d – error of the part.

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This coefficient allows one to evaluate the technological capabilities for increasing part accuracy, regardless of the type and magnitude of errors.

It is known that in rigid technological systems, when the rigidity of the part is greater than the rigidity of the machine, the error decreases from operation to operation, whereas in non-rigid technological systems the errors of the workpiece can be copied to the part completely [8–10].

The influence of negative hereditary properties on the final characteristics of machined parts should be either eliminated or limited. Therefore, technological heredity should be controlled by setting up such processing conditions in operations that would guarantee production of the part with the required accuracy.

One of the significant errors for low rigidity shafts is the crookedness of the longitudinal axis. In order to determine ways to reduce this error, it is necessary to know the mechanism of its formation and changes occurring in the process.

Figure 1 shows the change in the crookedness of a shaft type part (runout in the middle section) (*a*) and the refinement coefficient (*b*) during the process. One can see that the refinement coefficient decreases during the transition from roughing to finishing operations. That is, the largest decrease in the error of the workpiece occurs in roughing operations. Further processing does not introduce a significant reduction.

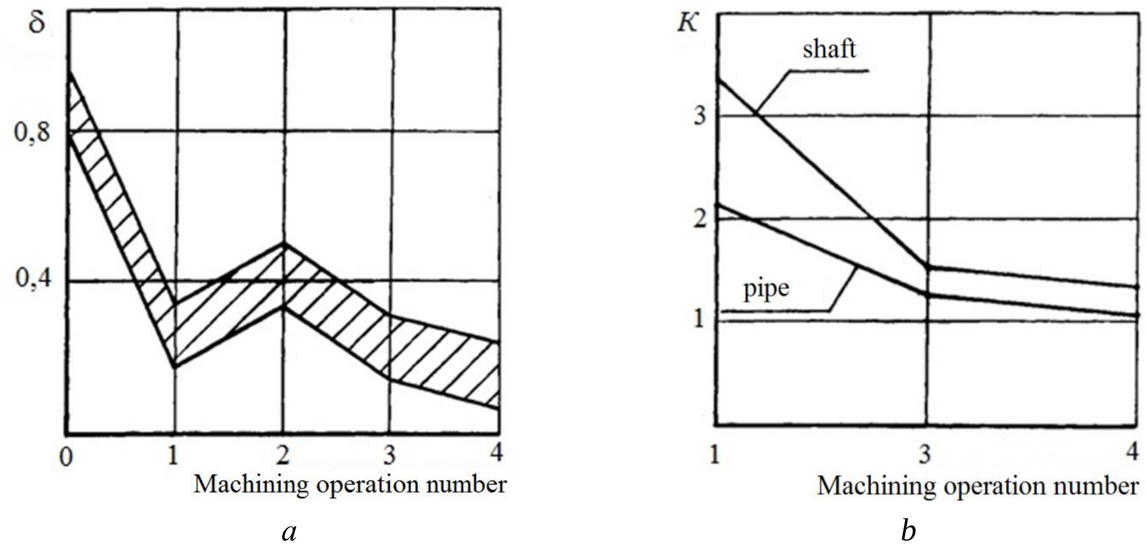

Figure 1. Change in the crookedness of a shaft-type part (runout in the middle section) (a) and the refinement coefficient of shaft and pipe type parts (b) along the process – machining operation: 1 – rough turning, 2 – thermotreatment, 3 – middle turning 4 – finish turning

Let us define the causes of this phenomenon. The deformation of a technological system with a linear elastic characteristic at a static load P is determined by the well-known formula

$$y = \frac{P}{j}, \tag{1}$$

where j – is the rigidity of the technological system.

The force acting on a technological system during machining is determined by the power-law dependence

$$P = C\, v^{u}\, s^{z}\, t^{x},$$

where C is a constant coefficient, v is the cutting speed, s is the feed, t is the cutting depth, u, z, x are the exponents.

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Deformation of the part under the influence of the cutting force reduces the depth of cut. Given the deformation of the system

$$P = C\,v^u\,s^z\,(t-y)^x, \tag{2}$$

where y – is the system deformation value.

Part errors – longitudinal axis out-of-straightness – is determined by the part middle section eccentricity e relative to the axis connecting the centers of the sections of the ends of the parts (Figure 2, *a*). Thus, the scheme of part error formation can be represented in the way presented in Figure 2, *b*.

As a result of workpiece a cross section center shift relative to the axis of rotation g by the value of e_p, the allowance along the circumference of the section is uneven. Consequently, the deformation of the technological system will also be uneven along the circumference. As a result, after machining, the result is the profile of part B with the center of the middle section b.

Let us describe the variation in a given allowance around the circumference by the equation

$$t = t_a + f(\omega) \tag{3}$$

where t_a is the average value of the depth of cut; $f(\omega)$ is a variable in the depth of cut as a function of the angle of rotation.

Figure 3 shows a diagram for determining the law of change of law of variation t. From the triangle

$$t = R - r_d, \quad R = \sqrt{r_p^2 + e_p^2 - 2r_p e_p \cos c}, \quad c = 180 - \omega - b, \quad b = \sin^{-1}\left(\frac{e_p}{r_p}\sin\omega\right)$$

Figure 4 shows the results of calculating the variation in t_1 by the angle of rotation of the part. It is seen that the law of variation is close to sinusoidal.

We approximate the variable value of the cutting depth by a sinusoidal function

$$f(\omega) = e_p \sin(\omega).$$

Figure 4 shows the results of approximation. It is evident that the two curves are practically superimposed on each other (the inset shows a fragment of the curves on an enlarged scale). The largest approximation error does not exceed 4.5 % (Figure 5)
Therefore, dependence (3) can be represented as

$$t = t_a + e_p \sin(\omega) \tag{4}$$

where e_p is the eccentricity of the workpiece; ω is the angle of rotation of the part.

Substituting equation (4) into (1), we obtain

$$P = C\,v^u\,s^z\,[t + e_p \sin(\omega) - y]^x \tag{5}$$

Let us expand expression (5) in the Maclaurin series with respect to y and $e_p\sin(\omega)$. Given only linear terms, we obtain

$$P = C\,v^u\,s^z\,[t^x + xt^{x-1}e_p \sin(\omega) - xt^{x-1}y] \tag{6}$$

As the calculations showed, the linearization error of function (5) in the range of possible values of y and $e_p\sin(\omega\tau)$ for any possible values of v, s, t is not more than 7.5 %.
After substituting (6) in (1) we obtain the equation

$$y = \frac{Cv^{-u}s^z t^x}{j + xCv^{-u}s^z t^x} + \frac{xCv^{-u}s^z t^{x-1}e_p}{j + xCv^{-u}s^z t^{x-1}}\sin\omega$$

Thus, under the influence of a variable cutting force due to a variable allowance around the circumference of the part, a change in the strain

$$y_2(\omega) = \frac{xCv^{-u}s^z t^{x-1}e_p}{j + xCv^{-u}s^z t^{x-1}}\sin\omega$$

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relative to the middle position occurs

$$y_1 = \frac{Cv^{-u}s^z t^x}{j + xCv^{-u}s^z t^x}.$$

The amplitude of the oscillation determines the error of the part. Given that $j >> xCv^{-u}s^z t^{x-1}$ we obtain

$$e_d = \frac{xCs^z t^{x-1} e_p}{jv^u}.$$

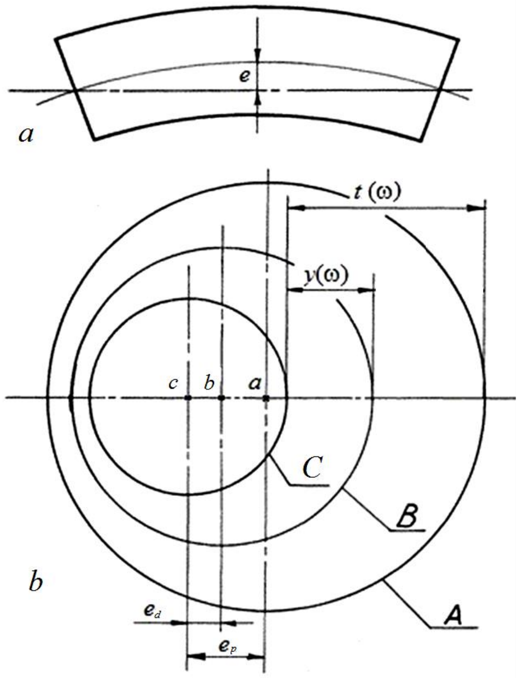

Figure 2. Scheme for determining the error in the longitudinal (a) and transverse (b) sections.

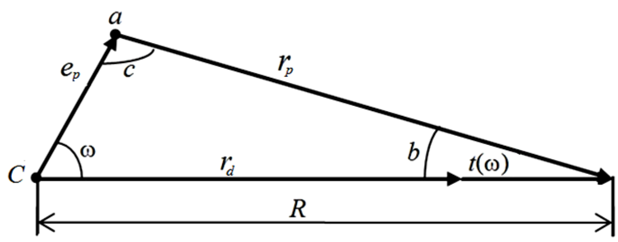

Figure 3. Scheme for determining the law of variation t: a – workpiece axis, c – workpiece rotation axis (spindle axis), e_3 – workpiece eccentricity relative to the rotation axis, r_p – workpiece radius, r_d – part radius, R – distance from the center of rotation to the workpiece outer surface, ω – workpiece rotation angle (spindle).

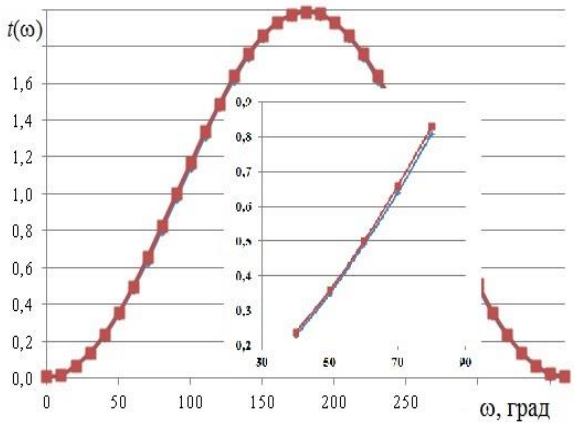

Figure 4. Change of cutting depth by rotation angle: ■ – calculated value, ◆ – approximation.

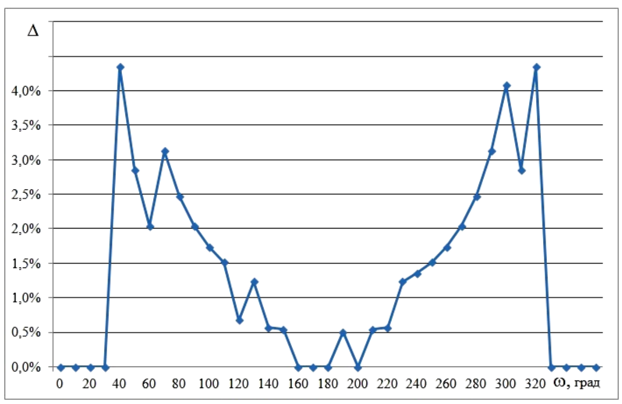

Figure 5. Change of approximation error (Δ) by rotation angle.

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Hence, the refinement coefficient is defined as

$$K = \frac{jv^u}{xCs^z t^{x-1}} \tag{7}$$

From dependence (7) one can see that with increasing rigidity of the technological system and cutting speed, the feed refinement coefficient increases. The influence of the depth of cut depends on the exponent *x* (Figure 6).

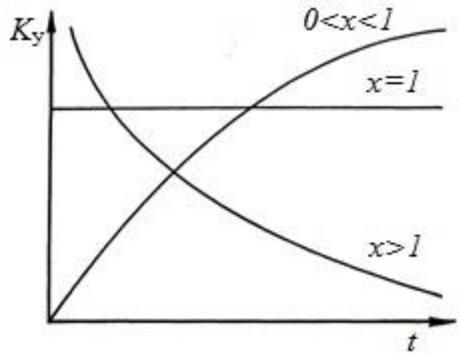

Figure 6. The nature of the dependence of the refinement coefficient on the cutting depth for various *x*.

For $0 < x < 1$, the exponent at *t* is less than zero, and the refinement coefficient increases with increasing depth of cut. For $x > 1$, the influence of the level on K_y is inverse. At $x = 1$, the refinement coefficient does not depend on the depth of cut.

3. Conclusion

For existing tool materials, the exponent *x* at the cutting depth in the formula of the cutting force *P* is in the range of 0.7–0.9 (range $0 < x < 1$). As the depth of cut decreases, the refinement coefficient decreases. Therefore, when switching from rough operations (large cutting depths) to finishing (small cutting depths), the refinement coefficient becomes smaller.

References

[1] Chengyan Zhang, Sicheng Jiao and Lixin Wang 2018 *Conference on Frontiers of Materials Synthesis and Processing* **493**

[2] Pereverzev P P and Akintseva A V 2016 *Russian engineering research* **12** pp 1048–53

[3] Xiao Q-B, Wan M et al 2020 *Robotics and Computer-Integrated Manufacturing* **64** 101949

[4] Lv L, Deng Z et al 2020 *International Journal of Mechanical Sciences* **1** 105543

[5] Grechishnikov V A, Pautov G A, Yurasov S Y and Yurasova O I 2017 *Russian engineering research* **3** pp 270–2

[6] Kremleva L V, Malygin V I and Lobanov N V 2016 *Russian engineering research* **12** pp 991–4

[7] Azimov B and Sulyukova L 2018 *XII International scientific and technical conference 'Applied Mechanics and Systems Dynamics', IOP Conf. Series: Journal of Physics: Conf. Series* **1210** 012003

[8] Świć A, Wołos D, Gola A and Smidova N 2019 *Tehnicki Vjesnik* **3** pp 256–63

[9] Karabulut A 2010 *Journal of the faculty of engineering and architecture of Gazi university* **2** pp 257–65

[10] Swic A, Wolos D et al 2014 *Applied Mechanics and Materials* **613** p 357